Micro-stages for Precision Positioning

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論文内容要約

This thesis presents micro-stages for precision positioning, including linear rotary (Z-θ_Z) stages, an XY stage and a corresponding displacement sensor for precision positioning.

In Chapter 1, the background, challenges and the motivation of this research are presented. A precision positioning stage is a micro/nano-positioning system capable of precise motion in moving and positioning an object with a relatively high resolution and accuracy. With the miniaturization of the precision systems, it is required to make a multi-axis micro-stage (Z-θ_Z or X-Y), which can fit in a space on the order of several centimeters, while achieving a sub-micrometer-scale resolution over a millimeter-scale moving range. Conventional multi-axis stages are generally stacked by single-axis stages, which have large enough moving ranges. However, the compactness of the stage is limited by the stacked structure of the stage and it has been difficult for a conventional stage to achieve both a compact size and a large moving range. On the other hand, a piezoelectric actuator (PZT) is one of the most well-used actuators for micro-stages because of its small size. A PZT also has the advantages such as fast response, high stiffness, high resolution and relatively large force output. However, the moving range of a PZT is typically less than 100 μm, which is too small to satisfy the requirements on the moving range of the micro-stage. Some PZT-based ultrasonic motors have been proposed to expand the moving range of a PZT stage beyond that of the PZT actuator for Z-θ_Z two-axis positioning. In this type, a shaft of the motor is driven by a pair of two-axis ultrasonic actuators so that the shaft can be rotated around and moved in the axial direction simultaneously or independently. However, high voltages need to be applied to the actuator to increase the friction force between the actuators and the shaft. Furthermore, it is difficult to tune the resonator and adjust the pre-load of the ultrasonic motor. The impact friction drive mechanism of using PZTs has also been proposed to achieve a millimeter-scale moving range in a linear stage. In such a mechanism, a moving element, which contacts with a friction element mounted on a PZT, is moved by an impact friction force for a large moving range. However, it is difficult to reduce the stage size because the impact friction drive mechanism requires a complicated pre-load sub-mechanism for adjustment of the contact force between the friction element and the moving element.

The motivation of this research is to develop multi-axis micro stages with compact sizes as well as long moving ranges. A PZT-based impact friction driving unit is utilized for two-axis driving. The driving unit is composed of two PZTs arranged perpendicularly to each other for Z-θ_Z or X-Y two-dimensional driving. A permanent magnet is employed as the friction element to support and drive the moving element without any additional pre-load sub-mechanisms. Therefore, the sizes of the stages can be made compact by using the developed driving unit. Based on the principle of impact friction drive, the stages can position a millimeter-scale stroke by repeating the moving stroke of the PZTs. By changing the structure of the moving element, the driving unit can be used for construction of linear-rotary (Z-θ_Z) stages and XY stages.

In addition, for precision measurement of the XY micro-stage, some typical displacement sensors, which include the laser interferometer sensors, the capacitive displacement sensors and the strain gauges, are commonly used as feedback sensors for the closed-loop control of micro/nanopositioning systems. With regard to the XY micro-stage, the compact mechanical assemblies would not allow a space for integrating laser interferometer systems or capacitive displacement sensors even though their resolution is high. On the other hand, a strain gauge sensor is appropriate for embedding into the stage as the feedback sensor regarding its small size and relatively low cost. The typical commercial strain gauge is a thin metal foil that the resistance would be changed with applied strain. Strain gauges can measure strain levels from a few micro-strain to over 100000 micro-strain. However, various errors due to temperature effects, bonding errors, lead wire effects, and transverse sensitivity may affect the accuracy of the measurement. Another type of the conventional strain gauge is the semiconductor strain gauge, which processes higher gauge factor than the metal foil strain gauges. However, the semiconductor strain gauges are easily affected by the ambient temperature, which is difficult to compensate and limits their widely use in experimental analysis.

To overcome disadvantages of conventional strain gauges, some institutes have developed a Cr-N thin-film as the strain gauge material. In this research, a Cr-N thin film displacement sensor is proposed for precision positioning of the XY micro-stage. The Cr-N thin film is sputtered directly on one side of a zirconia plate to form a full Wheatstone bridge circuit with four active strain

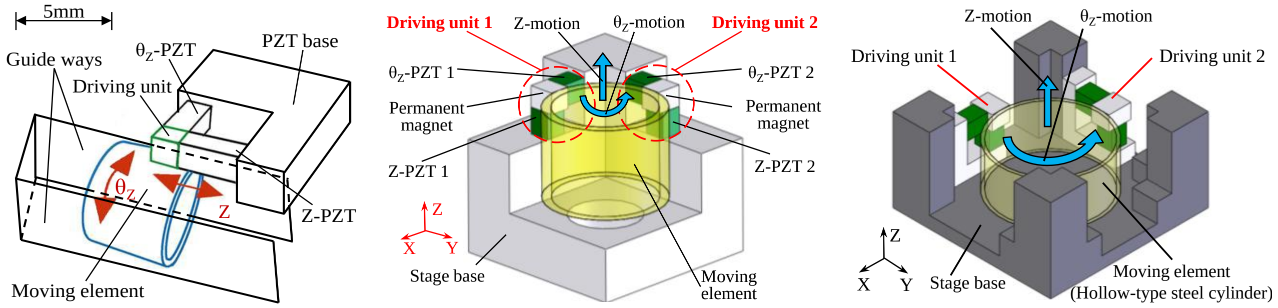
gauges. By measuring the deformation of the zirconia plate, the strain gauges can detect the displacement of the stage. The Cr-N film materials have several attractive properties, such as high temperature endurance, high sensitivity and high gauge factor. Drift, creep and hysteresis can also be suppressed because no adhesive is used. Therefore, the main objectives of this research are summarized as follows:

- Development of Z-θ_Z micro-stages which are composed of a novel two-axis driving unit and a hollow steel cylinder as the moving element.
- Development of an XY micro-stage by using the two-axis driving unit.
- Characterization and velocity improvement of the XY micro-stage
- Development of a Cr-N thin-film displacement sensor for precision positioning of the XY micro-stage.

In Chapter 2, a novel driving unit with a simple structure is presented. The driving unit is composed of two PZTs arranged perpendicularly to each other for Z-θ_Z two-dimensional driving. High-frequency triangular wave voltages are applied to the PZTs as the drive voltages of the stage for generation of the triangular-shaped impact friction motion. When the PZTs are driven along or around the Z-axis rapidly by the drive voltages, the moving element can be moved or rotated. To solve the problem of the complicated pre-load sub-mechanism in the conventional impact friction drive, a hollow steel cylinder and a permanent magnet are used as the moving element and the friction element of the stage, respectively. As the result, the hollow steel cylinder can be supported by the magnetic force without using any additional pre-load sub-mechanisms, which greatly simplifies the stage configuration. In this chapter, three types of linear rotary stages are described. The type 1 employs only one driving unit and two surfaces for driving the moving element, but vibration may occur due to the gap between the surface and the moving element (Fig. 1(a)). Thus, in type 2 (Fig. 1(b)), two driving unit are employed to construct a linear rotary stage. To improve the bonding layer of the PZTs, another type (type 3) is constructed by using the Bakelite as the L-shaped base for the driving unit to bond the PZTs. The millimeter-scale moving ranges of the stages have also been demonstrated by experiments. On the other hand, in type 3 of the linear rotary stage (Fig. 1(c)), for enhancement of the stage velocity, the transfer function of the micro-stage with the voltage applied to the PZT as the input and the PZT displacement as the output, is established. An improved waveform of the input voltage can be obtained based on the established transfer function for getting a triangular-shaped PZT displacement, which is an ideal waveform for the impact friction motion. The characteristics of the stage velocity before and after the improvement of the input voltage were verified and the effectiveness of the improved input voltage for enhancement of the stage velocity was confirmed.

In Chapter 3, an XY micro-stage (Fig. 2), which has a compact size of 24 mm (X) × 24 mm (Y) × 5 mm (Z), is designed and constructed for precision positioning of light weight objects. Aiming to achieve both a fair positioning resolution on the order of tens nanometres and millimetre-scale stroke, a design study of the XY micro-stage has been carried out. A driving unit, which consists of two PZTs and a friction component made by permanent magnet, is mounted on the center of the stage base for driving the stage moving plate made by steel in the X- and Y-directions based on a friction drive mechanism. The moving plate is attached on the friction component by the magnetic force. Leaf springs, which are used as suspensions, are employed to guide the X- and Y-directional motions of the moving plate over a range of ±1 mm in both directions. Following the design study, a prototype of the stage system has been developed, and its design concept has been verified in experiments.

Chapter 4 describes the movement cases of the XY stage. The movement of the stage is divided into four cases at different frequencies. In the low frequency, the stage moves slowly with the movement of the driving unit. With the applied triangular wave voltage, the stage moves forward and backward with a vibration motion. The ultimate position of the stage keeps still in this case. When the frequency reaches a certain value, the stage still moves with the movement of the PZT in the slowly increasing phase of the voltage, but there is slippage in the rapidly decreasing phase. Most of the conventional research has been focused on this case but neglected that the stage can move in a "slip-slip" case in higher frequency. In this case, if the frequency is not higher enough, the backward motion of the stage occurs and the movement of the stage will vibrate when moving forward. When the frequency becomes



(a) Type 1 (b) Type 2 (c) Type 3

Figure 1 The linear-rotary micro-stages

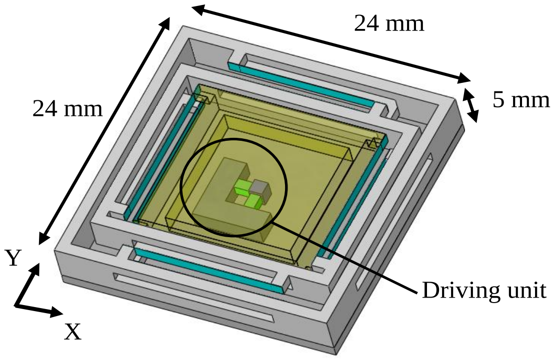


Figure 2 The XY micro-stage

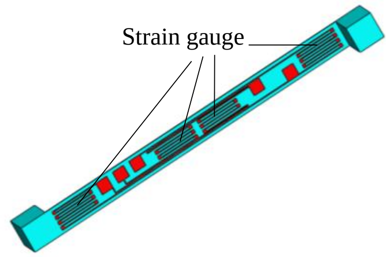


Figure 3 The Cr-N thin film displacement sensor

higher enough, the backward motion is eliminated due to the inertia of the stage. This is the case a friction drive mechanism desired, in which the stage can be driven smoothly. Then, in this chapter, the nonlinearity of the stage movement caused by the deflection of the stage is also described. Finally, the enhancement of the stage velocity is presented by using the method in Chapter 2.

In Chapter 5, the crosstalks between X- and Z-axes as well as X- and Y-axes are presented. The crosstalk between X- and Z-axes only exists in low frequency and can be neglected in smooth "slip-slip" case of the stage movement. Due to the inclinations of the target surfaces which may be caused by the assembly errors of the stage, including the assembly error of the stage parts and the assembly error of the target itself, the inclinations of the X- and Y-surfaces should be evaluated before experiments of the crosstalk. By subtracting the inclinations, the crosstalk between X- and Y-axes can be investigated experimentally. The crosstalk may be due to non-perpendicularity of the two PZTs caused by manufacturing errors and the motion crosstalk of the driving unit. To overcome the crosstalk and nonlinearity of the stage movement, a Cr-N thin film displacement sensor is proposed (Fig. 3). A leaf spring made of zirconium oxide is employed as not only the suspension but also the substrate of the sensor. By finite element method (FEM), it was verified that the strain gauges can be arranged on the same side of the leaf spring. The modal analysis and geometric parameters on strain distribution of the leaf spring were also investigated by FEM. Thus, based on the simulation results, three configurations of the sensor are presented for comparison. The Cr-N thin-film as the strain gauge material is sputtered on the leaf spring to form a full Wheatstone bridge circuit with four active strain gauges. The experimental results show that the developed sensors can be used for sub-micrometer positioning of the stage. The type 3 of the sensor can achieve a highest sensitivity and resolution, so it is preferable for precision measurement of the stage. The size of the leaf spring is 14 mm(L) × 1 mm(W) × 0.1 mm(T), which means that the sensor can also be integrated into quantities of micro systems which require compact structures.

In Chapter 6, conclusions and achievements of this thesis are discussed.